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Single-Sensor Stereo Camera

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August 1991

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13. ABSTRACT *(Maximum 200 words)*
A conventional stereo camera system usually uses two sensors to capture the two different perspective views of an image to produce stereo effect. The two-camera system has its drawbacks however. This report discusses the approach to the design of a single-camera system to capture and produce a signal on a display for stereo viewing, thus eliminating the drawbacks in the two-camera approach.

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Table of Contents

Section **Page**

List of Figures

BACKGROUND

The display group of the Electronics Technology and Devices Laboratory of the U.S. Army carries out research, development and military applications of stereoscopic display technology for remotely operated systems such as tele-operated robotic arm and land-based vehicle controls. The work includes equipment development, experimentation, and evaluation, and investigation of the feasibility and applicability of various stereoscopic display systems for the different military systems and environments. This report describes the research effort for the development of a stereoscopic system that captures and displays video in stereo from the use of a single sensor.

INTRODUCTION

3-D or stereoscopic effect requires two distinct views of an image, one for each eye of the viewer. Conventional stereo systems use two cameras, separated by an inter-ocular distance, to capture the two perspective views. The two-camera system has its drawbacks, however. This report presents the approach of using a single camera to capture the two image views and to produce a signal on a display for stereo viewing. This method eliminates many of the drawbacks in the two-camera approach.

PROBLEMS WITH TWO-CAMERA APPROACH

In normal human vision each eye receives a separate and distinct view of the same scene. The brain processes the two views and converts them into one image with depth. This is known as stereopsis. To perceive the optimum stereo effect, however, the two images must be matched in terms of their brightness, alignment, focus, etc. These adjustments are performed automatically by our visual system. Similar adjustments are required in a stereo video system to produce good stereo effect. In a two-camera system these adjustments may include the following: 1) alignment of pixels, 2) match of optics, 3) match of automatic gain control (AGC), 4) match of video amp, 5) match of video sync.

1. Alignment of Pixels - Alignment of the two images is critical in stereo. In a system where stereo is based on horizontal parallax information, this generally requires perfect alignment in the Y direction and a parallax displacement of approximately 6 degrees in the X direction. To achieve these alignments the two-camera system requires delicate, cumbersome and highly flexible design in the mounting apparatus for the cameras to allow precise alignment adjustment and to provide the rigidity needed once it is aligned.

2. Match of Optics - The two-camera system requires two lenses (one for each camera). The matching of the two optics in terms of

the focusing, aperture opening, etc. are critical in stereo. Quite often the act of adjusting the lenses can disturb the delicate pixel alignment described in 1 above, resulting in long set up time. When zoom-telephoto lenses are used, the adjustment can be cumbersome.

3. Match of AGC - The brightness of the two images has to match in order to get good stereo effect. Most camera systems incorporate automatic gain control (AGC) to the video to control the brightness of the images as the camera moves from scene to scene with different brightness levels. If the AGC for the two cameras is not matched, the two images may result in different brightness, thus affecting the stereo effect.

4. Match of Video Amp - As with 3 above, the video amp of the two cameras has to match in order for the two images to have the same brightness.

5. Match of Video Sync - In order for two cameras to operate together in sync, the two would need to be gen-locked together. This generally requires extra electronics.

ADVANTAGES OF SINGLE-CAMERA APPROACH

In most two-camera systems, because of the needs listed above, much effort is required during equipment set up to obtain the optimum optical and mechanical alignment. This can be a problem when the alignment is subjected to disturbance such as in situations where multiple use/changes of lenses are required, and/or where vibration is a concern.

If one camera is used, these problems can be eliminated. The one-camera system described here uses optics and electronics to replace one of the cameras. All of the required matches listed above either do not exist, or can be eliminated during system fabrication, thus resulting in a system that is more versatile, much easier to operate, and requires less time for set up. Furthermore, without the need to match optics, the single-camera approach can easily be adapted for use with devices such as night-vision devices and/or telephoto lenses, thus increasing its usefulness.

THE SINGLE-CAMERA APPROACH

The idea behind the single-camera stereo system is to replace one of the two cameras in the two-camera system with optics and electronics. The method of producing stereo here is time-multiplexing as commonly used in many two-camera systems, in which the alternate left and right images are time-multiplexed in the alternate odd and even fields of the video. Figure 1 shows a diagram of the time-multiplexed stereo video signal. A display

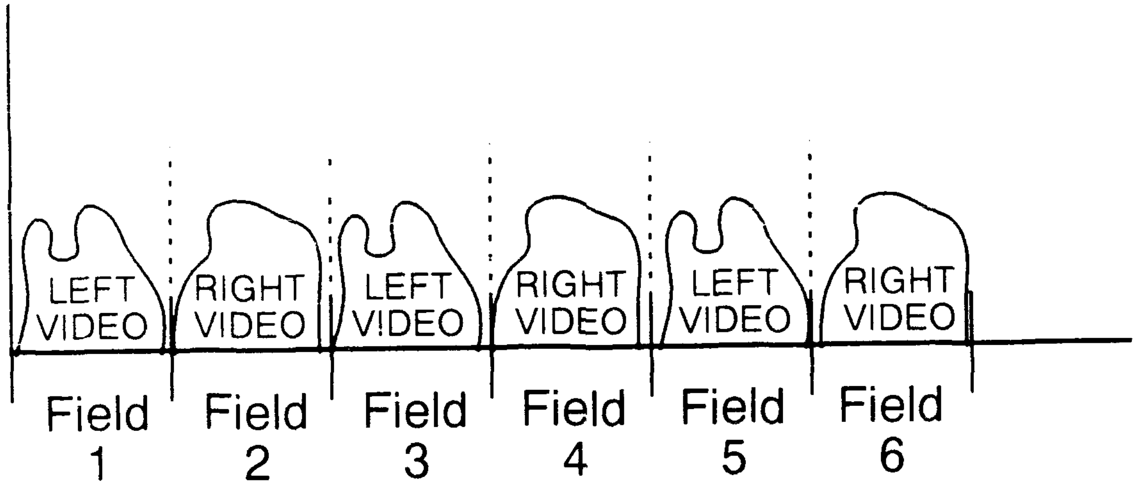


FIGURE 1. WAVEFORM OF TIME-MULTIPLEXED STEREO VIDEO SIGNAL

with this video input will produce a stereo effect when an observer views through special optics (shutter mechanism) which direct the correct perspective view of the image to each of the eyes. Figures 2A and 2B show the basic configuration and set up of the system, respectively. The optics in the front of the camera provide the left and right optical images to the camera as required for stereo operation. The polarizers and the liquid crystal (LC) shutter act as an optical switch, switching alternately to allow only one of the optical images to reach the camera at one time. The camera therefore sees a series of alternating left and right images. The switching rate is controlled by the electronics, and is synchronized with the field rate of the camera. The camera therefore sees only one of the images during any field period (time-multiplexing). The video output from the camera is then fed to a video memory for storage and scan conversion. The scan conversion is needed to provide flickerless viewing, as the camera does not operate at a high enough refresh rate. The output video to the display is a continuous series of alternating left and right images at a frame refresh rate of 120 Hz (i.e., 60 Hz for each image). As with the two-camera time-multiplexing stereo system, to view the video image in stereo, another set of polarizers and LC shutters is used in front of the display as shutter mechanisms to properly direct the correct image to the proper eye (i.e., left image to the left eye, and the right image to the right eye).

THE SINGLE-CAMERA SYSTEM HARDWARE

The prototype single-camera system was developed to prove the principle and to demonstrate the feasibility of the approach. The system was not intended for any particular application. As such, the hardware used in the single-camera system was mostly standard off-the-shelf type, commercially available, and easy-to-get parts, with the exception of the electronics that provide the frame storage, scan conversion and the control signals for the LC shutters. These electronics were obtained from another stereo system.

The components of the single-camera system include:

<u>Polarizer</u> - The polarizers used in front of the camera are both circular type polarizers. They were obtained from Edmund Scientific in large sheets and were cut to size for the fixture.

<u>LC Shutter</u> - Two shutters from two different manufacturers (i.e., Tektronix Corp. and StereoGraphics Corp.) were used. Both provided satisfactory results.

<u>Beam Splitter</u> - A 40-60 and a 50-50 beam splitter have each been used and both provided satisfactory results. They were both from Edmund Scientific.

<u>Mirror</u> - First surface type mirror from Edmund Scientific.

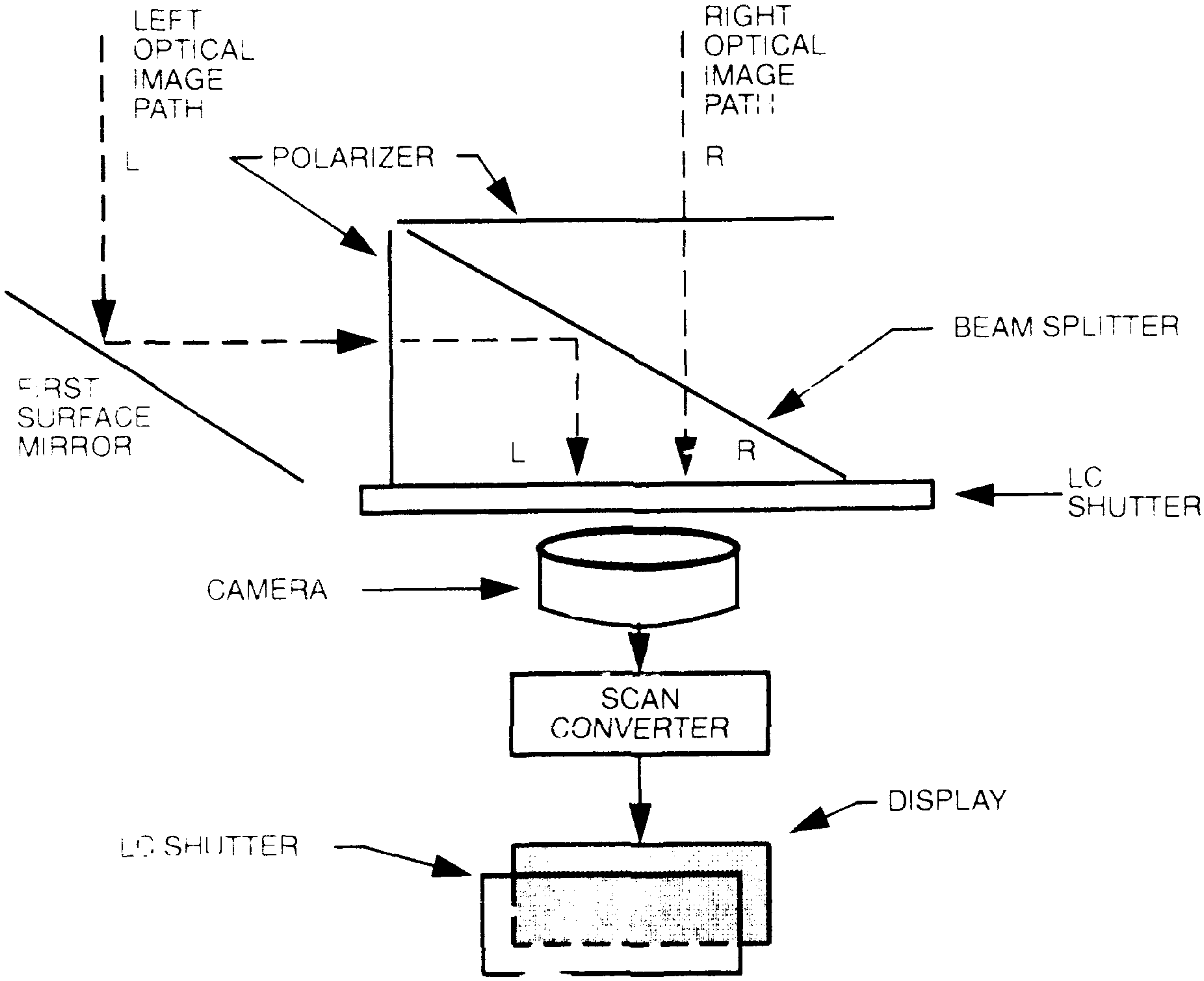


FIGURE 2A. SINGLE-CAMERA STEREO SYSTEM CONFIGURATION

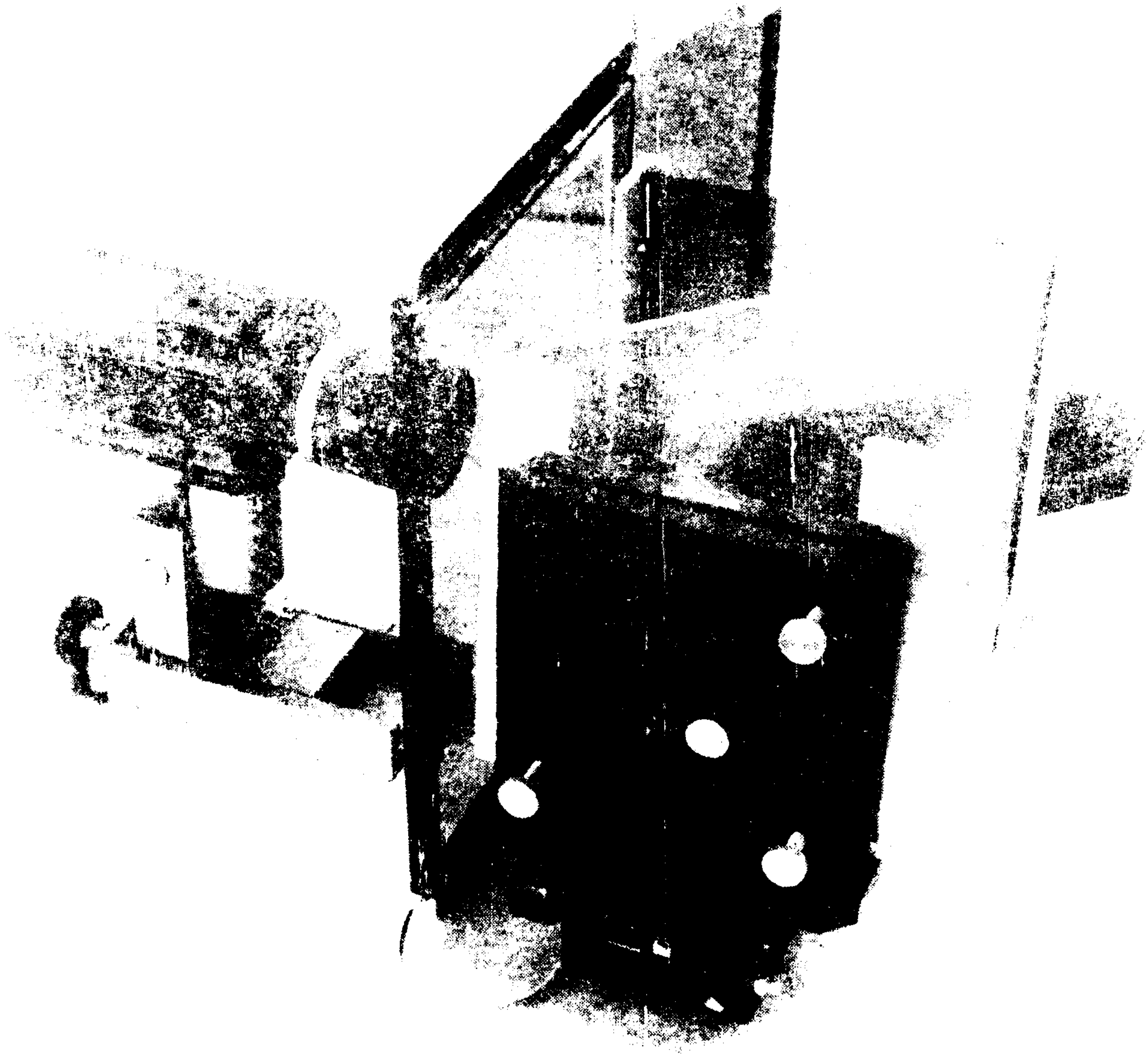


FIGURE 2B. SINGLE CAMERA STEREO SYSTEM SET UP

Optics - As shown in figures 2A and 2B, the optical paths of the left and right images are not equal; this resulted in a difference in the size of the two images going to the camera. Although this is not desirable for stereo, it was ignored for sake of simpler hardware set up. As pointed out earlier, the main objective of the project was to demonstrate the proof of principle. Futhermore, when the point of interest or object is far away, the difference becomes negligible. This was indeed the case as the resultant stereo image obtained from the system showed no noticeable difference in the size of the two images for objects beyond 20 feet.

Camera - Ordinary NTSC-type black-and-white (both CCD and vidicon type) video cameras were used. Different cameras exhibited different characteristics; as a result, the operating speed of the system had to be adjusted accordingly (see details in Design Consideration section).

Electronics - The electronics that provide the video storage, scan conversion and control signals for the whole system were taken from an existing system, with modifications to provide the necessary signals and function needed for the single-camera operation. The original custom-designed circuit was intended to be used as a two-camera stereo system capable of driving a special militarized EL display. It has all the necessary video memory and scan conversion functions needed for the single-camera system. Modifications were made to the circuitry to generate the needed control signals for the LC shutters, timing for the camera, memory, system synchronization, etc.

Display - A militarized 320x240 EL display from Norden Systems, and multi-sync CRT monitor from Mitsubishi (model HL6905) were used. Both provided satisfactory results.

Display LC-Shutter - Two sets of shutter mechanisms for the display were used. Both performed satisfactorily. One set consisted of the same LC-shutters used for the camera and a pair of passive polarizer eyeglasses. In this configuration, the LC-shutter was placed in front of the display and the observer looked through the passive eyeglasses. The other used active eyeglasses, and had both the LC-shutter and the passive polarizers built into one unit.

SYSTEM OPERATION AND DESIGN CONSIDERATIONS IN THE SINGLE-CAMERA SYSTEM

As shown in figure 2A the prototype system consists of three basic parts, namely, the optics, camera, and electronics, each performing a particular function. The following is a description of each of the parts, their interrelationships, operation and design considerations, and associated constraints.

<u>The Optics</u> - The purpose of the optics was to provide the left and right optical images to the camera, in such a way that they are in sync with the video fields of the camera, as shown in figure 1.

The optical images were obtained with optics consisting of polarizers, mirror, beam splitter and LC shutter in a setup shown in figure 3. The R and L are the right and left optical images, respectively. After passing through the circular linear polarizer, each of the light paths became circularly polarized. Since the same type of polarizers were used in each of the paths, the two light paths going to the beam splitter have the same direction of polarization. However, going to the LC-shutter, the two became opposite polarized, as the left path changed its polarization 180 degrees after reflecting off the beam splitter. The LC-shutter acts as an optical switch, switching between two states. One state allows one direction of the polarized light to go through, the other state for the other polarization. The LC-shutter is controlled by a signal that is in sync with the camera. In this way, the left and right optical images are gated synchronously with the operation of the camera.

<u>The Camera</u> - Much of the system design was centered around the camera. The purpose of the camera was to provide a video signal carrying the left and right image information in a time-multiplexed fashion. Such waveform as shown in figure 1 shows that during one time slot (i.e., one field time) there is a distinct left or right video image, and there is no overlapping or mixing of the two images in any one field. With the available cameras we used in the experiment, however, we were unable to obtain such waveform. The cameras were ordinary NTSC type cameras designed for normal use (i.e., non-stereo) and their speeds were too slow for stereo operation. When they were used in stereo mode, the result was an output signal with adjacent field interferences. Following is a detailed description of the problem.

Speed of Sensor - The speed of the sensor element refers to the speed for the capture/integrate and transfer of the image after the sensor was exposed to the image. To obtain the waveform shown in figure 1 it is necessary to accomplish the image capture/integration and transfer functions within one field time. However, none of the cameras used in the prototype system exhibited such speed. Figure 4 shows typical responses of two of the cameras used. In both cases, the camera was exposed to a light source of the same intensity. As shown, camera A required two field times to obtain its maximum registration, whereas camera B required three field times. From this it is obvious that the continuous pair of alternating left and right signals of figure 1 is not possible, as the speed of the available cameras was too slow to obtain maximum registration in one field time.

Decay Time - The decay time of the sensor element refers to the time required for a complete decay of the image in the sensor element after it reaches the maximum registration. Figure 5 shows

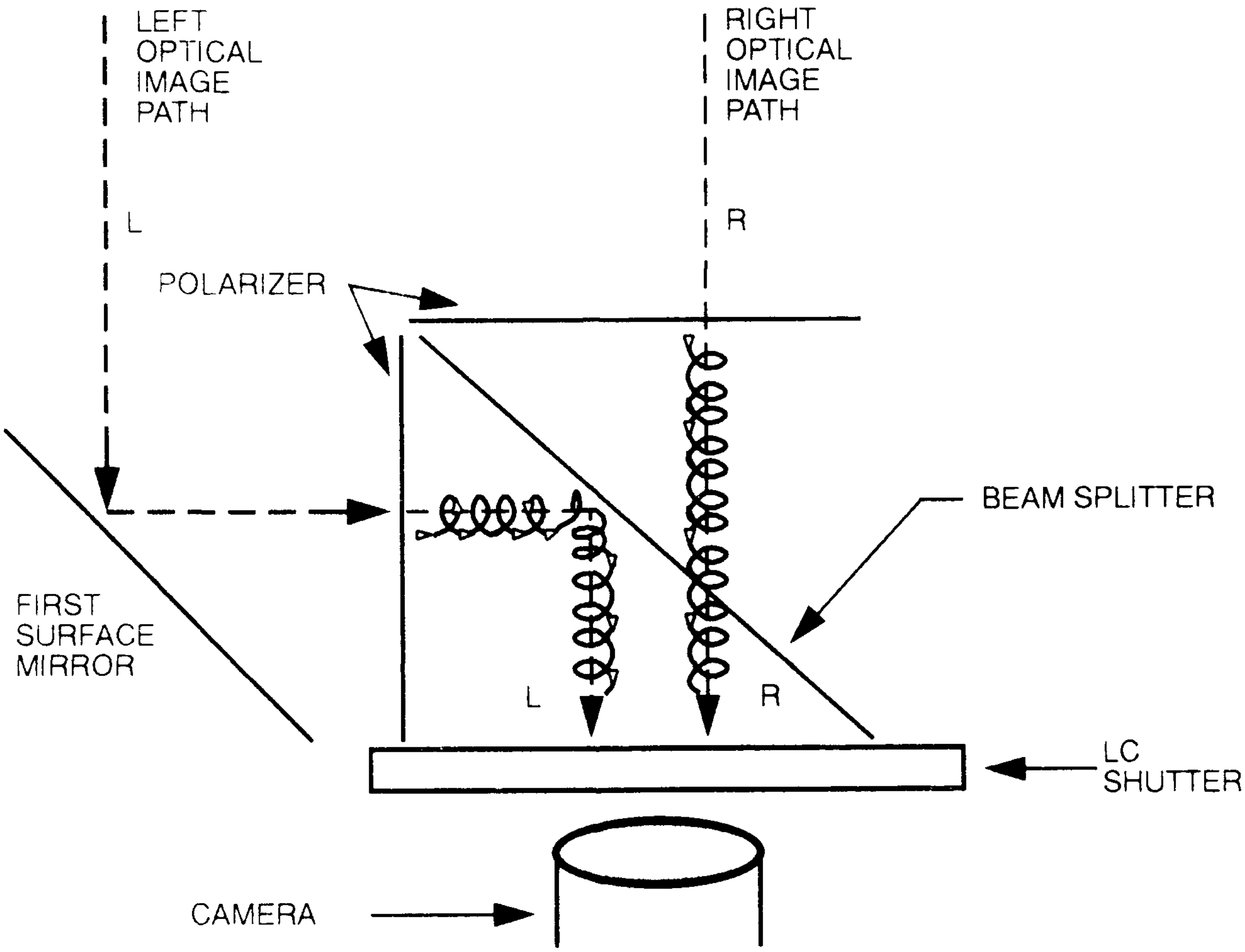
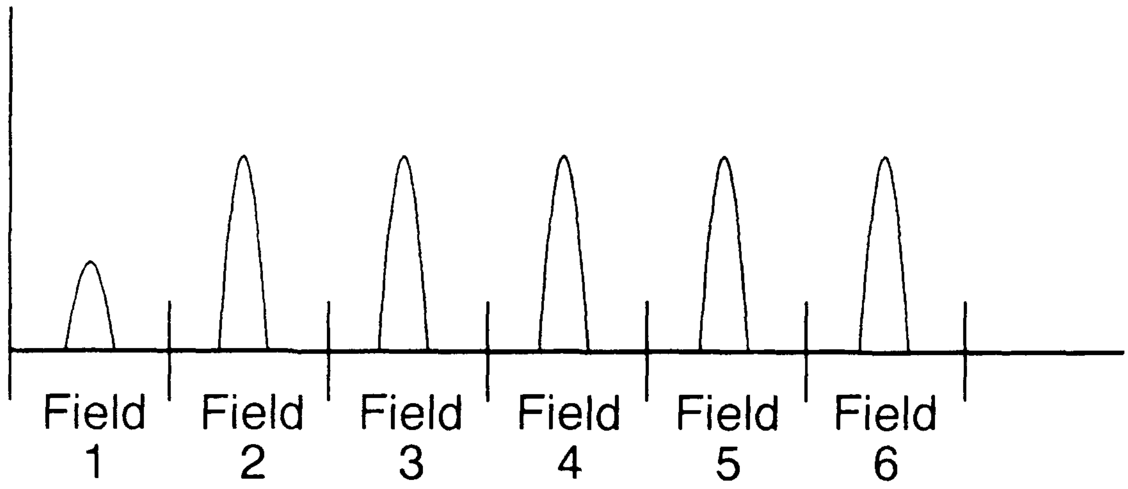
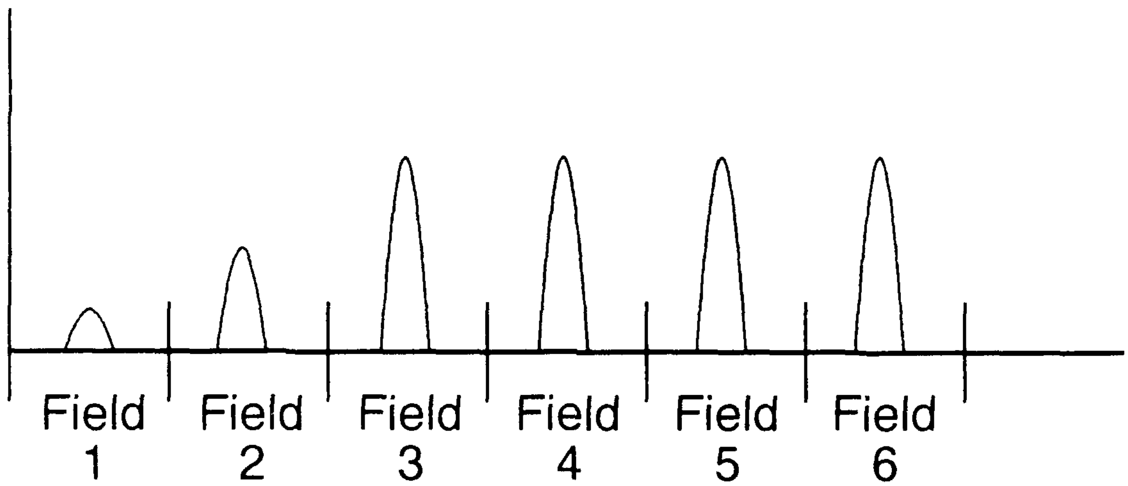


FIGURE 3. POLARIZATION OF LEFT AND RIGHT OPTICAL PATHS



CAMERA (A) RESPONSE



CAMERA (B) RESPONSE

FIGURE 4. TYPICAL CAMERA CAPTURE/ INTEGRATION RESPONSE (Rise Time)

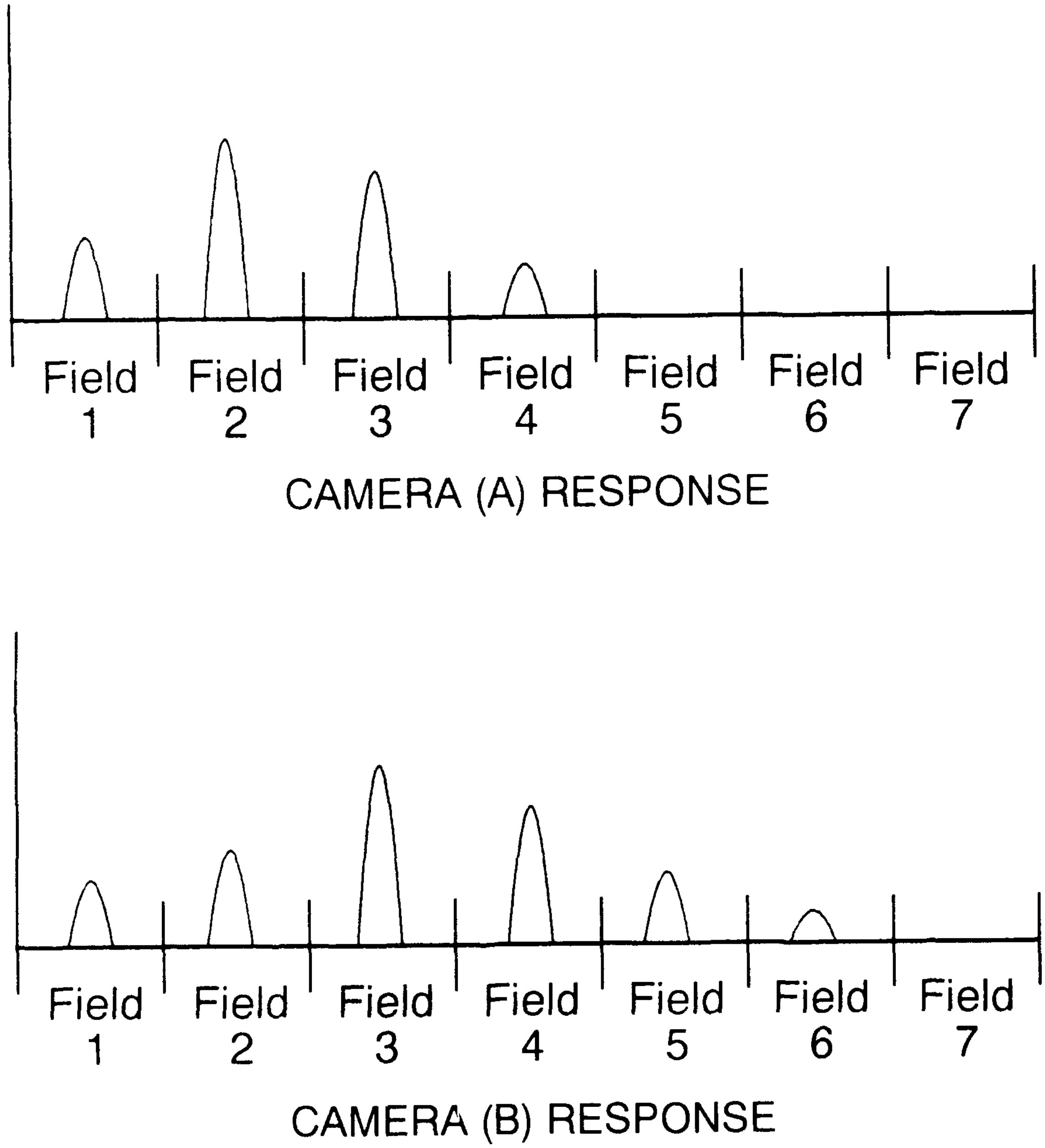


FIGURE 5. TYPICAL CAMERA DECAY TIME

typical responses of two of the cameras used. In both cases, the camera was exposed to a light source of the same intensity for a duration to allow it to reach maximum registration, and then the light source was immediately removed. As shown, camera A required two field times for a full decay whereas camera B required three.

The integration and the decay time together contribute to a condition referred to here as interfield interference. This is the interference caused by the overlapping of signals from one field to signal(s) on the adjacent field(s) if the timing of the left and right images to the camera is not properly controlled with respect to the camera's integration and decay time. Figure 6 shows a diagram of a video waveform with interfield interference caused by slow decay time. L's and R's are the left and right video images, respectively. As shown, it takes three field times for either the L or R to decay completely, and if the image of the other stereo pair were exposed to the camera sensor prior to complete decay of the first image, overlap would occur. The interference can get more complicated when integration time is taken into account.

To obtain a non-overlap time-multiplexed stereo signal with slow speed camera, the waveform shown in figure 1 has to be modified. The modification involved the slowing down of the operation of the system to accommodate the camera speed. Basically, the left and right images going to the camera are controlled in a manner such that the maximum registration of the exposed image in the camera occurs just after the prior image has completely decayed. Figure 7 shows a diagram of such condition. As shown, the waveform contains both interfield interference and distinct left and right video signals at each field. Maximum registration (without interference) for the left image occurs at fields 3 and 9, and right image at fields 6 and 12. These fields (i.e., fields 3, 6, 9, 12, etc.) containing the distinct left and right video images from the camera output are then selected and gated to the video buffer for storage, and later scan-converted to a higher (i.e., 120 Hz) refresh rate for display. Thus, instead of the continuous pair of alternating left and right distinct video images in figure 1, the signal going to the video buffer/scan converter is a noncontiguous pair of alternating left and right distinct videos. Figure 8 shows a diagram of the signal.

The Electronics - Aside from providing the functions of video storage and scan conversion, the electronics also provide the signals for the system control, timing, and synchronization. These timing controls are as follows:

LC-shutter Control for the Camera - This is the control for the timing of the LC-shutter, determining when and which of the left or right optical images passes through to the camera input. To obtain the waveform of figure 7, the timing must be in sync with the operation of the camera to avoid interfield interference. Figure 9 shows a diagram of the signal with respect to the video.

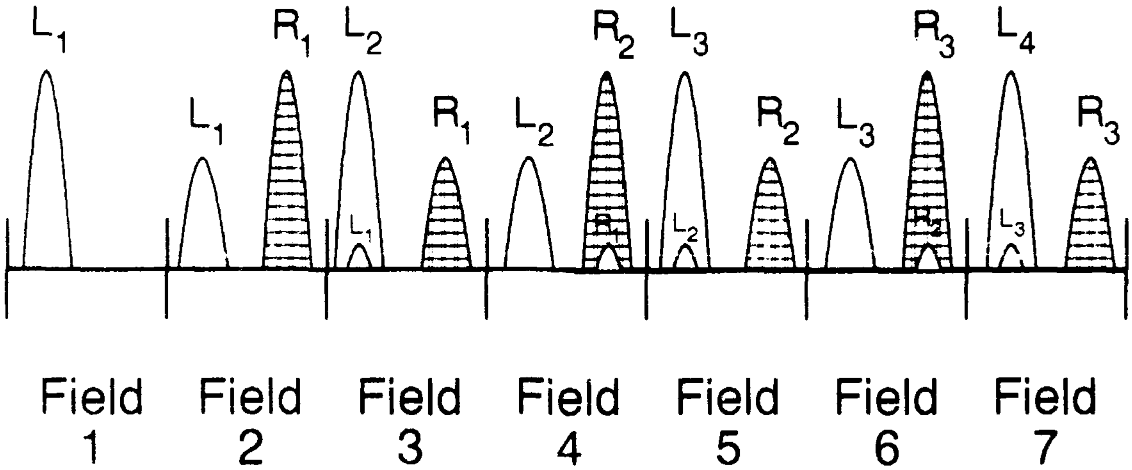


FIGURE 6. VIDEO WAVEFORM WITH INTERFIELD INTERFERENCE CAUSED BY SLOW DECAY TIME OF SENSOR

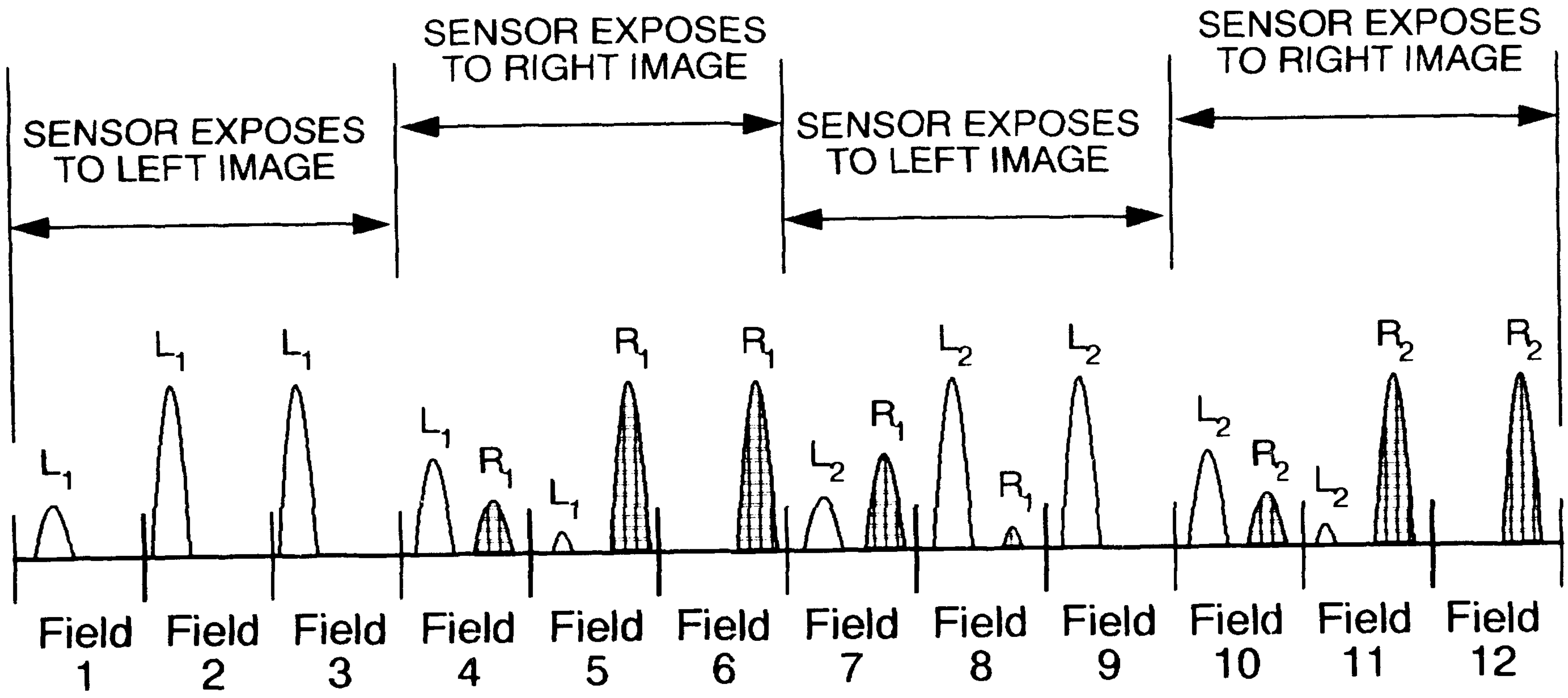


FIGURE 7. WAVEFORM OF VIDEO SIGNAL CONTAINING BOTH INTERFIELD INTERFERENCE AND DISTINCT LEFT AND RIGHT IMAGES.

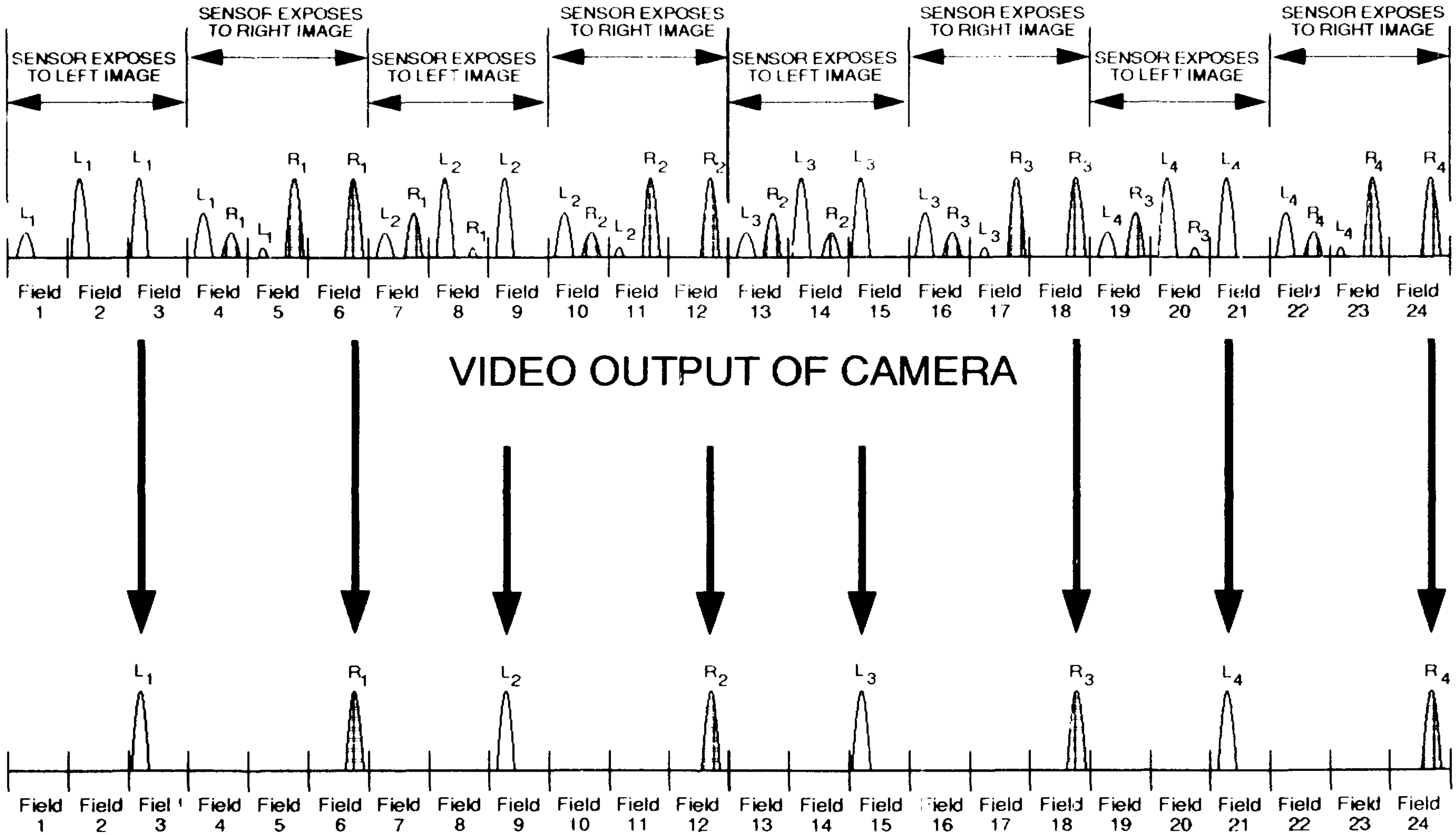
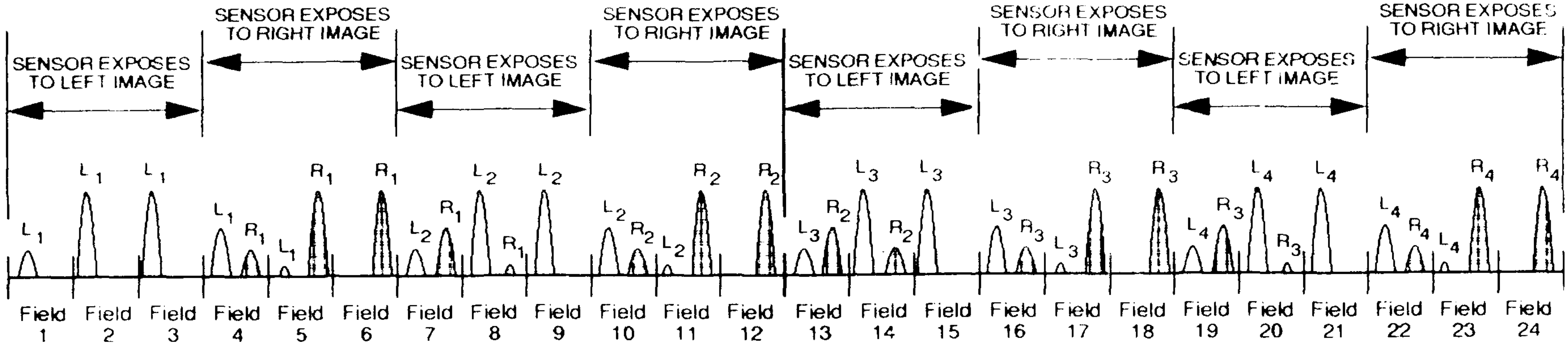


FIGURE 8. WAVEFORM OF SELECTED FIELDS FROM CAMERA OUTPUT TO VIDEO BUFFER INPUT



VIDEO OUTPUT OF CAMERA

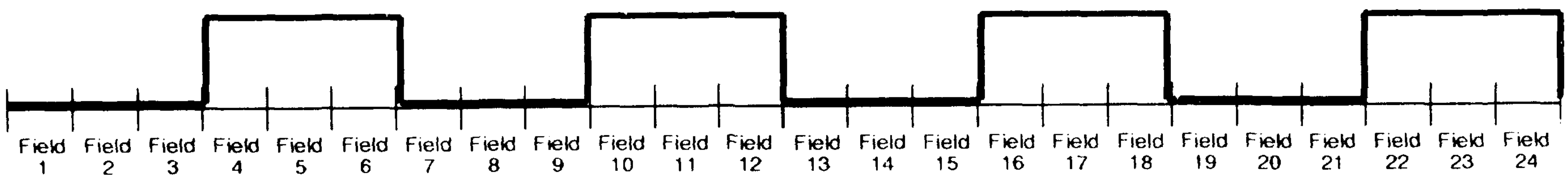


FIGURE 9. CONTROL SIGNAL TO LC-SHUTTER (CAMERA) IN RELATION TO CAMERA OUTPUT

Sampling Control - This is the signal to provide control for the selection of the particular video field of the camera output that goes to the video memory. As with the above, the timing must be in sync with operation of the camera, to avoid interference. Figure 10 shows a diagram of the sampling control signal.

LC-Shutter Control for the Display - This is the signal for controlling the switching of the LC-shutter in front of the display, directing the correct perspective image's view to the proper eye. As such, it must be in sync with the video's refresh rate. Figure 11 shows a diagram of the signal with respect to the output video.

RESULTS

Results of the prototype single-camera stereo system demonstrated the satisfactory performance of the system in producing stereo images. Live stereo videos were observed on a CRT and a flat panel EL display, with the system using both the active goggle and the passive eyeglasses with the LC-shutter in front of the display. Aside from the noticeable jerky movement as a result of the slowing down of the camera's refresh rate to compensate for its slow speed, the stereo effect was very vivid. The scan converter provided a display refresh rate of 110 Hz, therefore no flicker was observed since each eye sees a 55 Hz signal. The resultant differences in the size of the two images due to the optics setup was noticeable, as anticipated. However, for objects beyond approximately 25 feet it became insignificant. This is not a problem since the optics can be altered accordingly without any difficulty. Different cameras have been used with the system (with system operating speed adjusted accordingly); they all produced similar results. Various lenses, including a telephoto lens were used. Use of the telephoto lens really demonstrated the benefits of the system's ability to quickly and easily zoom in and out without the need for any image adjustment/matching.

CONCLUSIONS

This prototype single-camera stereo system has successfully demonstrated the feasibility of the single-camera approach for producing stereo video images using the time-multiplexing technique. With this approach, many of the inherited problems associated with the two-camera system can be eliminated. The advantages of the single-camera system include the following:

1. Perfect mechanical alignment of pixels.
2. Perfect match of optics.
3. No need to match AGC electronics.
4. No need to match video amplifiers.
5. No need to match video syncs (gen-lock).

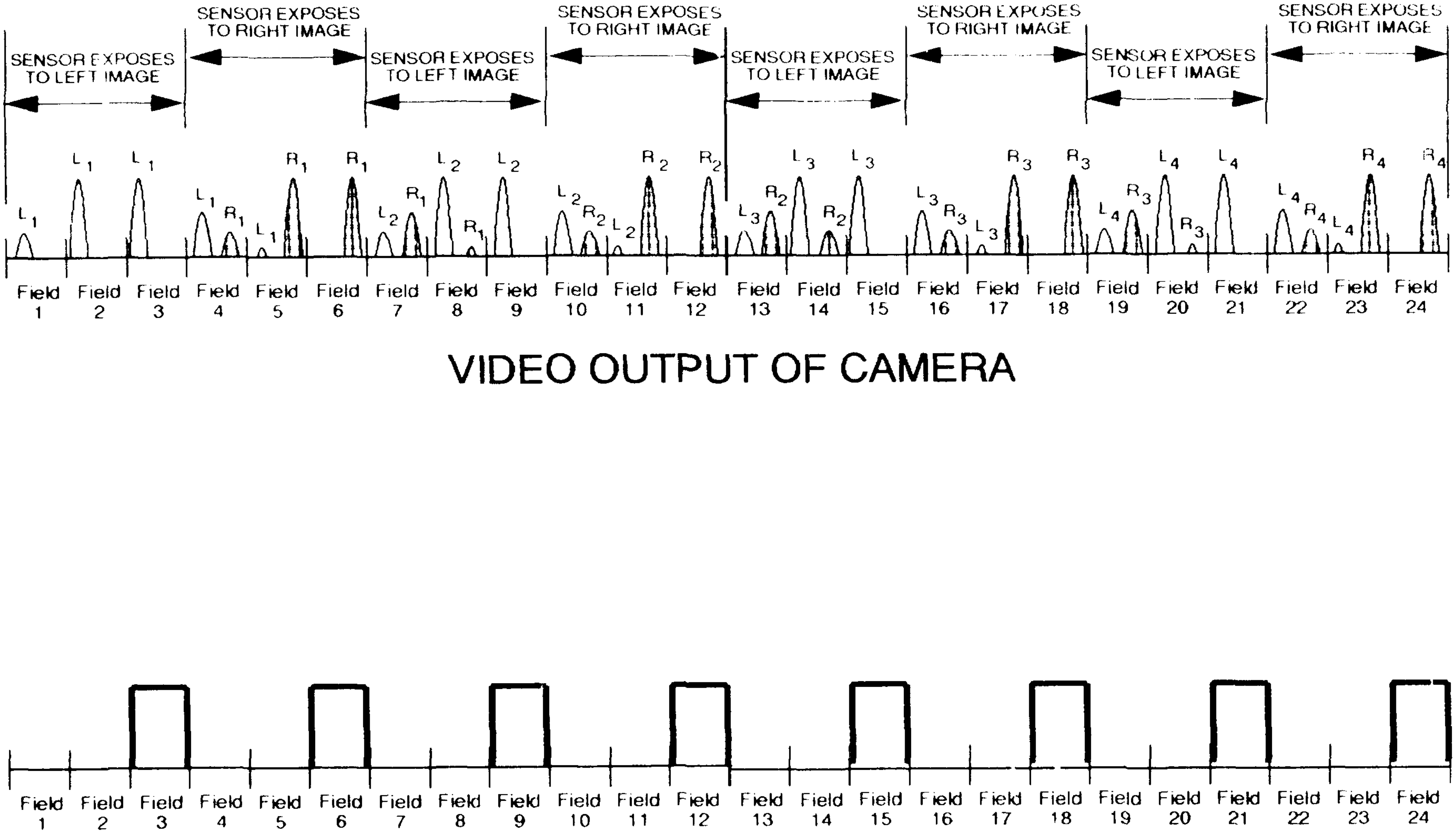


FIGURE 10. SAMPLING SIGNAL IN RELATION TO CAMERA OUTPUT

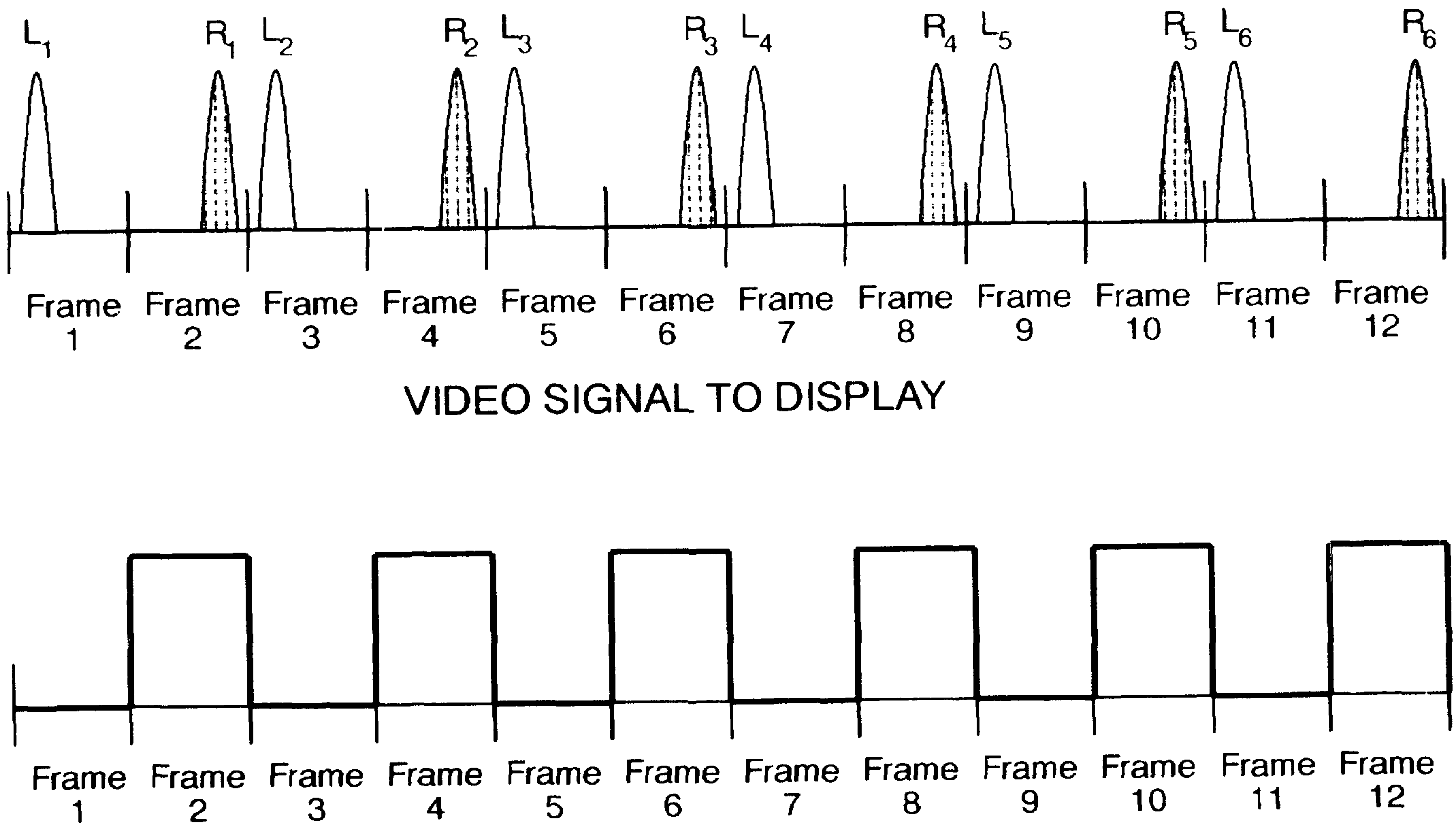


FIGURE 11. CONTROL SIGNAL TO LC-SHUTTER (DISPLAY) IN RELATION TO SCAN CONVERTER OUTPUT

As a result, the single-camera approach provides better system versatility, easier system operation and set up, and a wider range of usage including the use with zoom-telephoto lenses and night-vision devices.

FUTURE SYSTEM CONSIDERATIONS

As with the two-camera system, the single-camera has its own drawbacks. To improve the performance of the single-camera system, these areas need further investigation. The most obvious areas are in the sensor. They are as follows:

1. Frame Mode of Operation - The prototype system used a standard NTSC type camera which operated in field mode (i.e., each image was limited to the resolution of a field). This is fairly discernable when adjacent fields contain the same information and the output is interlaced, however, when the camera is used in a time-multiplexed mode for stereo, the resultant low resolution stereo images were highly noticeable (i.e., resolution equal to half that of the non-stereo). If the sensor can operate in frame mode, this would increase the resolution by 2X.

2. Higher Speed - The response time of the sensor including capture/integration, transfer, and decay time, should be much improved. The ideal speed would accomplish all of the capture/integration, transfer, and decay functions in one frame time so that there is no interframe interference and a waveform similar to that of figure 1 can be obtained.

3. 120 Hz Operation - The NTSC type camera, even if it has the above integration/decay speed, can only operate at 60 Hz, the NTSC standard. To provide flickerless viewing, a non-NTSC type camera would be needed to operate with a minimum of 120 Hz so that each eye sees a non-flicker 60 Hz signal.

With such a sensing device, there would be no need for video memory or scan conversion, resulting in less hardware. The camera output can connect directly to the display for viewing.

Another area is in the optics. The optics used in the prototype system suffered enormous light loss through the polarizers, beam splitter, mirror and LC-shutter. If all the optics can be made into one piece with all the components laminated together (and/or with the use of dichromic materials), much of the lost light can be saved, resulting in brighter and better image quality.

Another area is the investigation of the feasibility of a system with full color capability, since color enhances the effect on stereo.

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